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Do U.S. Environmental Protection Agency Water Quality Guidelines for Recreational Waters Prevent Gastrointestinal Illness? A Systematic Review and Meta-analysis

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Despite numerous studies, uncertainty remains about how water quality indicators can best be used in the regulation of recreational water. We conducted a systematic review of this topic with the goal of quantifying the association between microbial indicators of recreational water quality and gastrointestinal (GI) illness. A secondary goal was to evaluate the potential for GI illness below current guidelines. We screened 976 potentially relevant studies and from these identified 27 studies. From the latter, we determined summary relative risks for GI illness in relation to water quality indicator density. Our results support the use of enterococci in marine water at U.S. Environmental Protection Agency guideline levels. In fresh water, *Escherichia coli* was a more consistent predictor of GI illness than are enterococci and other bacterial indicators. A log (base 10) unit increase in enterococci was associated with a 1.34 [95% confidence intervals (CI), 1.00–1.75] increase in relative risk in marine waters, and a log (base 10) unit increase in *E. coli* was associated with a 2.12 (95% CI, 0.925–4.85) increase in relative risk in fresh water. Indicators of viral contamination were strong predictors of GI illness in both fresh and marine environments. Significant heterogeneity was noted among the studies. In our analysis of heterogeneity, studies that used a nonswimming control group, studies that focused on children, and studies of athletic or other recreational events found elevated relative risks. Future studies should focus on the ability of new, more rapid and specific microbial methods to predict health effects, and estimating the risks of recreational water exposure among susceptible persons. *Key words:* bathing water, diarrhea, gastrointestinal illness, indicator organisms, meta-analysis, swimming, systematic review, water quality. *Environ Health Perspect* 111:1102–1109 (2003). doi:10.1289/ehp.6241 available via *http://dx.doi.org/* [Online 14 April 2003]

Since the 1950s, numerous studies have examined the association between recreational water quality and health outcomes. Many of these studies have reported an increased risk of illness associated with exposure to recreational water. Several have related the level of contamination in the water, as measured by indicators of water quality, with the magnitude of risk. Despite extensive research on this topic, uncertainty remains about how water quality indicators can best be used in the regulation of recreational water environments. In 1986, the U.S. Environmental Protection Agency (U.S. EPA 1986) published recommended water quality criteria for recreational waters, which proposed the use of enterococci in marine water and enterococci and/or *Escherichia coli* in fresh water as indicator organisms. That report recommended regulatory levels based on geometric means of at least five samples over a 30-day period of 35 colony-forming units (cfu)/100 mL and 33 cfu/100 mL for enterococci in marine and fresh water, respectively; and 126 cfu/100 mL for *E. coli* in fresh water (U.S. EPA 1986). Fecal coliforms, which had been previously proposed for use as an indicator, were no longer recommended. The studies upon which these revised guidelines were based (Cabelli 1983; Dufour 1984a) have been criticized (Fleisher 1992), and the draft revised World Health Organization (2001) guidelines have been developed using more recent controlled studies (Kay et al. 1994).

Few attempts have been made to summarize and evaluate the existing literature in a systematic and quantitative framework. Pruss (1998) concluded that the literature strongly suggests a dose–response relationship between fecal contamination and the risk of gastrointestinal (GI) illness but did not examine the relationship between specific water quality indicators and health outcomes.

Our primary goal in this systematic review was to evaluate the evidence linking specific microbial indicators of recreational water quality to specific health outcomes under nonoutbreak conditions. Secondary goals were to identify and describe critical study design issues, to quantify and evaluate sources of heterogeneity among the studies, and to evaluate the potential for health effects at or below the current suggested regulatory standards.

Methods

Literature search. Our literature search included several computerized databases: MEDLINE (http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?db=PubMed), BIOSIS (www.biosis.org), OLDMEDLINE (http://gateway.nlm.nih.gov/gw/Cmd), and EMBASE (http://openaccess.dialog.com/med/) for the period from 1950 to the present. We searched dissertations using the UMI/ProQuest Digital Dissertation Database (http://wwwlib.umi.com/dissertations/gateway). The search terms included key words "recreational water and health" and subject heading searches for "environmental pollutants, adverse effects" or "water pollution, adverse effects." We consulted experts in the field and reviewed the bibliographies of relevant studies for additional references. We reviewed the titles and abstracts of all studies in the searches for relevance, and we flagged potentially relevant studies for further full text review.

We retrieved and reviewed manuscripts for studies whose abstracts appeared to examine health effects in relation to swimming and microbiologic water quality. We also obtained studies that were not in English, provided the abstract was available in English. Conference proceedings, doctoral dissertations, reports, and other unpublished studies when identified were also obtained.

Selection criteria. Studies were included in the review based on the following criteria:

Water exposure. Studies that measured exposure to marine (ocean) or fresh water (lakes, rivers, ponds) were included. Studies of exposure to chlorinated water sources were excluded.

Water quality measures. At least one measure of microbial water quality had to be reported by the authors. Studies that reported water quality but did not relate these measures to human health were excluded.

Health outcomes. Studies had to report at least one measure of health that could potentially be associated with water quality. Studies that only examined infection (i.e., as measured by serology) and examined only typhoid and/or polio were excluded. Although we abstracted data for all types of health outcomes, in this analysis we focused on GI illness because it has

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been the most extensively studied and because it is the outcome for which current recreational water quality guidelines have been developed.

Study design. We focused on epidemiologic studies that quantified the relationship between water quality indicators and GI illness under endemic, or nonoutbreak, conditions. Risk assessments, case series, case reports, and descriptions of outbreaks were excluded because such studies do not provide evidence of quantitative associations between specific indicators and health outcomes under endemic conditions.

Data abstraction. Two authors (T.J.W. and N.P.) independently abstracted data from all identified studies and conferred to resolve uncertainties. For each study, the following information was abstracted: water quality measure and level, water type (marine, fresh), how water quality was measured in relation to exposure (i.e., same day, at the time of swimming, or over the entire study period), population studied, geographic location, study size, study design, symptom measured, covariates measured, how swimming exposure and outcome were measured, relative risks, and confidence bounds. Correlation coefficients, regression coefficients, *p*-values, and 95% confidence bounds were also abstracted. When relative risks were not reported, data were abstracted to calculate the relative risk (defined as the ratio of the proportion ill in the exposed to the proportion ill in the unexposed) and its 95% confidence interval (CI). When a *p*-value was provided rather than a CI, the CI was calculated using published formulas (Greenland 1998). When multiple symptoms were reported, we selected the results based on the following guidelines: a multisymptom definition (e.g., diarrhea occurring with either fever or vomiting), if presented, was preferentially chosen; if only specific symptoms were presented, results associated with "diarrhea" were selected.

Data analysis. We conducted separate analyses for each combination of water quality indicator, health outcome, and water type (fresh vs. marine). When studies reported results within a range of indicator values, we recorded the median value of the reported range as the exposure value. We formed exposure categories based on quartiles, tertiles, or the 50th percentile of the exposure values, depending on the number of estimates available. When a single study reported more than one effect estimate within each of our defined exposure categories, we selected the results associated with the highest exposure measure within each exposure category. For example, if our lowest category included indicator values within a range of 1–20, and a single study reported effect estimates for both the 1–10 and 11–20 range, we selected the effect estimates associated with the 11–20 range. We did this so that a single study would not have greater influence on a single summary relative risk simply because it reported more effect estimates within a smaller range. To evaluate the U.S. EPA guideline values, exposure categories were developed for risk estimates above and below these levels.

We calculated summary relative risks as a weighted average using a random-effects model (DerSimonian and Laird 1986). We included adjusted relative risks whenever available. Heterogeneity was assessed for each exposure category using the Q statistic (DerSimonian and Laird 1986).

To evaluate the continuous relationship between the measured water quality indicators and the effect estimates, we conducted a weighted regression for each water quality indicator wherein the indicator level (log base 10) was modeled as a continuous predictor of the natural log of the relative risk. To account for study size, the models were weighted by the inverse of the standard error of the natural log of the relative risk. Because there were few effect estimates available for nonfecal and viral indicators of water quality, we conducted this regression analysis only for the bacterial fecal water quality measures.

To investigate sources of variability among the studies, we used a random-effects meta-regression model (Thompson and Sharp 1999). The dependent variable was the natural log of the relative risk for GI illness. Independent variables included in the initial model were water type, geographic location (United States, United Kingdom, other European countries, Asia, Africa, Australia), control group (swimmers or nonswimmers), swimming definition (required head immersion or did not require), adjustment for covariates, age of study population, method of exposure measurement (self-report, direct observation, or event participation), length of follow-up period, and study location. The water quality indicator density was included in all models. The final model was selected by excluding covariates with *p*-values > 0.2.

All analyses were conducted in Stata 7.0 for Windows (Stata Corporation 2002).

Results

We reviewed 976 abstracts or titles for relevance. Fifty-five of the 976 appeared relevant and were selected for further review. Of these, 27 (Table 1) were included in the final review. Of the 28 excluded studies, eight (Balarajan et al. 1991; Calderon and Mood 1981; Fewtrell et al. 1994; Harrington et al. 1993; Jessop et al. 1985; New Jersey Department of Health 1989; Seyfried et al. 1985a; van Asperen et al. 1995) were excluded because the data analysis and reporting were deemed insufficient, 11 were duplicated in other articles or reports (Bandaranayake et al. 1995; Cabelli et al. 1975, 1979, 1982; Dufour 1984b; Jones et al. 1991; Ktsanes et al. 1981; Public Health Laboratory Service 1959; Pike 1990, 1991; Zmirou et al. 1990), five reported outcomes that were not of immediate interest (typhoid, polio, serologic results, or public health impact) (D'Alessio et al. 1981; El-Sharkawi and Hassan 1979; Fleisher et al. 1998; Philipp et al. 1989; Taylor et al. 1995); one examined a water quality measure not reported in any other study (cyanobacteria) (Pilotto et al. 1997); and three did not measure GI illness (Calderon and Mood 1982; Charoenca and Fujioka 1995; Fleisher et al. 1996).

Table 1. Studies included in the review.

Reference	Location	Water type	Sample size	Study type
Stevenson (1953)	USA	Fresh	5,124	Cohort
Cabelli (1983)	USA	Marine	26,686	Cohort
Cabelli (1983)	Egypt	Marine	23,080	Cohort
Foulon et al. (1983)	France	Marine	4,921	Cross-sectional
Dufour (1984b)	USA	Fresh	21,777	Cohort
Philipp et al. (1985)	UK	Marine	247	Event
Seyfried et al. (1985b)	Canada	Fresh	3,967	Cohort
Fattal et al. (1986)	Israel	Marine	2,231	Cohort
Lightfoot (1989)	Canada	Fresh	9,296	Cohort
Ferley et al. (1989)	France	Fresh	5,737	Cohort
Cheung et al. (1990)	Hong Kong	Marine	18,741	Cohort
Alexander et al. (1992)	UK	Marine	703	Cohort
Calderon et al. (1991)	USA	Fresh	144	Cohort
von Schirnding et al. (1992)	South Africa	Marine	733	Cohort
Fewtrell et al. (1992)	UK	Fresh	516	Event
Pike (1994)	UK	Marine	16,569	Cohort
Corbett et al. (1993)	Australia	Marine	2,968	Cohort
Fleisher et al. (1993)	UK	Marine	509	Randomized trial
Kay et al. (1994)	UK	Marine	1,306	Randomized trial
Medema et al. (1995)	The Netherlands	Fresh	395	Event
Marino et al. (1995)	Spain	Marine	2,249	Cohort
Kueh et al. (1995)	Hong Kong	Marine	18,122	Cohort
Lee et al. (1997)	UK	Fresh	473	Event
McBride et al. (1998)	New Zealand	Marine	3,887	Cohort
van Asperen et al. (1998)	The Netherlands	Fresh	1,600	Event
Haile et al. (1999)	USA	Marine	11,686	Cohort
Prieto et al. (2001)	Spain	Marine	1,858	Cohort

Study methodologies and key characteristics. The sample size of the 27 studies ranged from 247 to 26,686 subjects. Seventeen studies took place in marine water, and 10 in fresh water (Table 1).

Study design. We identified four study designs: traditional prospective studies, prospective studies during recreational events, randomized controlled trails, and cross-sectional studies.

Eighteen of the studies included were traditional prospective studies (Table 1). In these studies, beach-goers were recruited and questioned about their swimming and exposure to water. They were contacted again 3 days to 1 month later and asked about health symptoms they experienced during this period. Water samples were collected periodically, usually at least once each interview day. Subjects were classified as swimmers and nonswimmers, and rates of illnesses in these two groups were compared.

Five of the selected studies were prospective studies of athletic or organized recreational events (Table 1). In these studies, event participants were recruited. The unexposed group consisted of bystanders, event organizers, or participants in a related event that did not involve swimming. Subjects were contacted after the event and asked about the occurrence of illness. Water quality was measured during the event.

A series of randomized trials were conducted in the United Kingdom in the 1990s (Fleisher et al. 1993, 1996; Kay et al. 1994). In these trials, subjects were randomly assigned by investigators to be swimmers or nonswimmers. Investigators observed swimmers who were asked to swim in a prescribed fashion. Water quality was measured at or near the time of swimming.

One cross-sectional study was identified (Foulon et al. 1983). In this study, subjects were questioned about their recent illnesses at the same time as they were questioned about their swimming in the past 4 days.

Exposure assessment. Most studies determined swimming exposure through self-report or through proxy self-report. Three studies reported having directly observed swimming behavior (Fleisher et al. 1993; Haile et al. 1999; Kay et al. 1994) and five determined exposure through participation in an event (Fewtrell et al. 1992; Lee et al. 1997; Medema et al. 1995; Philipp et al. 1985; van Asperen et al. 1998).

Definition of the unexposed group. Studies varied in the way they defined the comparison (unexposed) group. Some studies used nonswimmers for comparison, whereas others used swimmers in relatively better water (as measured by water quality indicators). Other studies included results from both types of comparison groups.

Water quality measures. Water quality measures were determined in one of three ways: *a*) on the day of exposure (Alexander et al. 1992; Cabelli 1983; Calderon et al. 1991; Cheung et al. 1990; Corbett et al. 1993; Dufour 1984a; Fattal et al. 1986; Fewtrell et al. 1992; Haile et al. 1999; Kueh et al. 1995; Lee et al. 1997; Lightfoot 1989; Marino et al. 1995; McBride et al. 1998; Medema et al. 1995; Philipp et al. 1985; Prieto et al. 2001; Seyfried et al. 1985b; von Schirnding et al. 1992); *b*) at the time of swimming (Fleisher et al. 1993; Kay et al. 1994; van Asperen et al. 1998); or *c*) aggregated over several days, weeks, or months (Ferley et al. 1989; Foulon et al. 1983; Pike 1994; Stevenson 1953). Although exposure was measured on each interview day for most studies, often it was aggregated in the analyses. This was particularly true for studies that compared illness rates between two or more beaches that differed in overall water quality over the entire study period.

Definition of swimming. The most common definition of swimming required submersion of the head in the water (Cabelli 1983; Calderon et al. 1991; Cheung et al. 1990; Corbett et al. 1993; Dufour 1984a;

Table 2. Summary relative risks of GI illness by level of exposure to indicators of water quality: marine water studies.

Indicator	Relative risk (95% CI), category level (1 = lowest; 4 = highest)[a] 1	2	3	4	Correlation coefficients (*r*, *p*-value)[b]
Fecal bacterial indicators					
Enterococci/fecal streptococci	1.58* (1.20–1.96)	1.61* (0.997–2.60)	2.45* (1.56–3.77)	1.95 (1.53–2.49)	0.82, < 0.001 (Cabelli 1983) 0.68, NG (Cabelli 1983)
Range (cfu/100 mL)	1–20	21–54	69–104	123–7,460	0.32, NS (Cheung et al. 1990)
Number of studies	8	6	7	7	
Fecal coliform	1.40 (1.05–1.88)	1.69* (0.88–3.2)	1.41* (0.87–2.28)	2.02 (1.46–2.77)	0.51, NG (Cabelli 1983) 0.49, NS (Cheung et al. 1990)
Range (cfu/100 mL)	2–65	77–300	310–550	598–2,000	0.26, NS (Kueh et al. 1995)
Number of studies	5	6	6	7	0.77, < 0.05 (Pike 1994)
E. coli	1.80 (1.30–2.50)	1.41 (1.06–1.88)	2.46* (1.31–4.65)		0.54, NG (Cabelli 1983) 0.74, NG (Cabelli 1983) (Egypt)
Range (cfu/100 mL)	2–54	55–290	320–5,207		0.51, < 0.05 (Cheung et al. 1990)
Number of studies	3	4	5		0.28, NS (Kueh et al. 1995):
Total coliform	1.15 (0.74–1.78)	1.79* (0.83–3.83)	2.08* (0.85–2.08)		0.65, NG (Cabelli 1983) 0.53, NS (Pike 1994)
Range (cfu/100 mL)	45–320	700–2,022	2,100–5,750		
Number of studies	3	5	4		
Nonfecal bacterial indicators					
Staphylococcus sp.	1.45* (0.2–10.76)	0.59* (0.21–1.68)			–0.25, NS (Marino et al. 1995) 0.095, NS (Kueh et al. 1995)
Range (cfu/100 mL)	1–175	250–1,114			0.19, NS (Cheung et al. 1990)
Number of studies	2	3			
Pseudomonas sp.	1.44* (0.44–4.73)	1.47* (0.28–7.86)			–0.05, NS (Marino et al. 1995) 0.59, NG (Cabelli 1983):
Range (cfu/100 mL)	0–17	26–220			0.21, NS (Cheung et al. 1990)
Number of studies	2	2			
Aeromonas sp.	3.86 (1.76–8.49)	3.27 (1.01–10.57)			0.52, 0.01 (Kueh et al. 1995) –0.23, NS (Marino et al. 1995)
Range (cfu/100 mL)	17	662			0.6, NG (Cabelli 1983)
Number of studies	1	1			

Abbreviations: NG, not given; NS, not statistically significant, *p*-value not provided; [a] Relative risk is the risk versus the summary relative risk for exposed (swimmers) versus unexposed in each category. [b] Values reported represent the correlation between illness and indicator density. *p-Value for test of heterogeneity < 0.2.

Fattal et al. 1986; Fleisher et al. 1993; Haile et al. 1999; Kay et al. 1994). Few studies measured duration and intensity of exposure. Those that did found that a higher risk of GI illness was associated with longer or more intense exposure (Corbett et al. 1993; Prieto et al. 2001) or with an increase in the number of times water was swallowed (Lee et al. 1997). More uniform exposure may be more likely in both controlled trials (Fleisher et al. 1993; Kay et al. 1994), where swimming exposure is prescribed and then observed by researchers, and studies of athletic events.

***Quantitative relationships between indicators and GI illness: marine water*. Bacterial indicators of fecal contamination.** Bacterial indicators of fecal contamination considered were enterococci/fecal streptococci, *E. coli*, fecal coliform, and total coliform (Tables 2 and 3). Although there was some trend toward increasing relative risk for all of the indicators, overall, the strongest trend was associated with enterococci. In the categorical analysis, the relative risk did not continue to increase in studies with densities greater than 104 cfu/100 mL, indicating a potential threshold for risk of GI illness. The relative risk of GI illness, although statistically elevated in all categories of *E. coli*, was greatest in the highest *E. coli* category (320–5,207 cfu/100 mL). A consistent increase in the relative risk was also observed for total coliform. Risk of GI illness was statistically elevated in the highest (598–2,000 cfu/100 mL) and lowest (2–65 cfu/100 mL) fecal coliform category, but only one of the four studies reported a significant correlation (Pike 1994).

Results from the weighted regression (Table 3) confirm an association between enterococci density and the natural log relative risk. The relative risk for GI illness increased 1.3 times for every log 10 increase in enterococci density. The relationship between enterococci and the log relative risk is also illustrated graphically in Figure 1. Significant associations were not identified with the other indicators, although positive associations between *E. coli* and total coliform were also observed.

Indicators of viral contamination. Two direct indicators of viral contamination in marine waters, enterovirus (or culturable enteric viruses), and bacteriophage were studied. Pike (1994) noted a strong correlation between enterovirus and GI illness ($r = 0.84$, $p < 0.05$). Because few studies (Alexander et al. 1992; Haile et al. 1999; Pike 1994) evaluated enterovirus, the results were collapsed into a single exposure category [range, 0.53–4.7 plaque-forming units (pfu)/10 L]. Enterovirus was a strong indicator for GI illness, producing a summary relative risk of GI illness of 2.15 (1.45–3.17)

Only two studies examined bacteriophage and GI illness in marine waters, and one study (von Schirnding et al. 1992) did not find sufficient numbers to conduct an analysis. The most detailed analysis in marine water was the studies conducted by Pike (1994). In this study, no significant correlations were reported.

Nonfecal indicators of water quality. Nonfecal indicators of water quality included *Staphylococcus* species, *Pseudomonas* sp., and *Aeromonas* sp. Two studies (Cabelli 1983; Kueh et al. 1995) found significant relationships between *Aeromonas* levels and GI illness, although Cabelli (1983) did not note a trend. *Pseudomonas* sp. and *Staphlyococcus* sp. were not associated with GI illness (Table 2).

***Quantitative relationships between indicators and GI illness: fresh water*. Bacterial indicators of fecal contamination** (Tables 3 and 4). *E. coli* was the only indicator clearly associated with an increase in the relative risk of illness in both the categorical analysis (Table 4) and the weighted regression (Table 3, Figure 2). No increase in relative risk was observed for high levels of enterococci compared with low levels. Risk for GI illness was elevated for both categories of fecal coliform, but no statistically significant correlations were observed. Illness was significantly elevated in the highest total coliform exposure category, but this was based on only one study (Ferley et al. 1989). In the weighted regression analysis, only *E. coli* was correlated with an increase in the relative risk (Table 3).

Indicators of viral contamination. Enterovirus was significantly associated with GI illness at both exposure levels. The summary relative risk was considerably elevated in the highest exposure category (relative risk = 4.11, 95% CI, 2.59–6.54), although one study (Lee et al. 1997) reported no correlation. GI illness was also elevated in both bacteriophage exposure categories.

Nonfecal indicators of water quality. Although elevated relative risks were observed in both categories of *Staphylococcus* sp., there appeared to be no trend with increasing levels. Contradictory results were observed for

Table 3. Model parameters from weighted linear regressions of the natural log relative risks as a function of indicator density (log base 10).[a]

Indicator	No.[b]	Intercept	Coefficient	*p*-Value	*r*[c]
Marine water					
Enterococci	28	0.099	0.30	0.05	0.37
Fecal coliform	22	0.86	–0.024	0.94	–0.017
E. coli	12	–0.071	0.25	0.24	0.37
Total coliform	12	–0.096	0.42	0.25	0.36
Fresh water					
Enterococci	8	0.54	0.0078	0.97	0.016
Fecal coliform	11	0.53	0.0058	0.98	0.0083
E. coli	5	–1.07	0.75	0.063	0.86
Total coliform	Too few estimates				

[a] Weights for the model were the inverse of the standard error of the natural log of the relative risk. [b] Number of effect estimates. [c] Correlation coefficient.

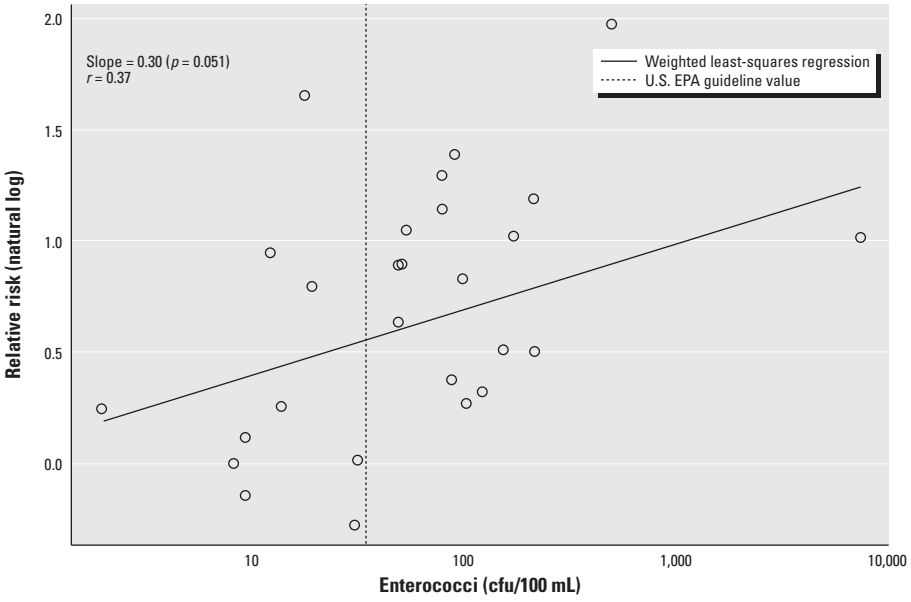

Figure 1. Scatterplot and weighted regression line (weighted by the inverse of the standard error of the natural log relative risk) of natural log relative risks of GI illness from marine water studies as a function of enterococci density.

Pseudomonas sp.: Ferley et al. (1989) observed a strong negative correlation of borderline statistical significance, whereas Lightfoot (1989) observed a positive correlation. Ferley et al. (1989) likewise observed a negative correlation with *Aeromonas* sp., but the relative risk at the highest category from the same study was elevated. This contradiction likely resulted from the use of geometric means of samples collected over the course of the summer for the relative risk calculation. The correlation, however, was apparently based on individual exposure measures assigned to individual swimmers.

Evaluation of current standards. **Marine water.** Summary relative risks for GI illness below the U.S. EPA–suggested value (U.S. EPA 1986) for both enterococci and *E. coli* were lower (and were not statistically significant), whereas relative risks above the suggested values were elevated (and were statistically significant). In contrast, the summary relative risk point estimate for fecal coliform exposure decreased slightly in studies with exposures above the guideline values compared with studies with exposures below this value.

Fresh water. Relatively few studies reported indicator densities above the guideline values. Summary relative risks both above and below the enterococci exposure guideline value were elevated for those exposures both above and below the enterococci guideline value (Table 5). Studies below the guideline value for *E. coli* were not associated with increased illness, whereas exposures above the guideline level were. Exposures above the previously suggested guideline for fecal coliform were also elevated (and of borderline statistical significance) compared with those below this value.

Table 4. Summary relative risks of GI illness by level of exposure to indicators of water quality: freshwater studies.

Indicator	Relative risk (95% CI), category level[a] Low	High	Correlation coefficients (*r*, *p*-values)[b]
Fecal bacterial indicators			
Enterococci/fecal streptococci	2.01* (1.18–3.41)	1.65 (1.38–1.98)	0.62, 0.02 (Ferley et al. 1989) 0.67, NS (Dufour 1984a) 0.1, NS (Lightfoot 1989)
Range (cfu/100 mL)	10–14	16–1,669	*p* = 0.069 (Seyfried et al. 1985b)
Number of studies	4	4	
Fecal coliform	1.73* (1.28–2.33)	1.84* (1.10–3.10)	0.38, 0.2 (Ferley et al. 1989) –0.081, NS (Dufour 1984a)
Range (cfu/100 mL)	22–110	200–18,612	0.19, 0.15 (Lightfoot 1989)
Number of studies	7	4	
E. coli	1.22 (0.99–1.51)	1.78 (1.45–2.20)	0.81, < 0.05 (Dufour 1984a) 0.18, 0.17 (Lightfoot 1989)
Range (cfu/100 mL)	45–170	187–204	
Number of studies	3	2	
Total coliform	0.7 (0.30–1.62)	2.40 (1.68–3.39)	0.46, 0.11 (Ferley et al. 1989)
Range (cfu/1100 mL)	786	24,461	
Number of studies	1	1	
Viral indicators			
Enterovirus	1.97* (1.20–3.22	4.11 (2.59–6.54)	
Range (pfu/10 L)	0–0.4	1–198.4	
Number of studies	2	2	
Bacteriophage	2.42 (1.85–3.17)	2.80 (1.30–6.02)	
Range (pfu/100 mL)	0.07–20	1,885	
Number of studies	2	1	
Nonfecal bacterial indicators			
Staphylococcus sp.	4.30 (2.60–6.94)	2.73 (1.32–5.63)	0.13, 0.34 (Lightfoot 1989)
Range (cfu/100 mL)	14	36–45	
Number of studies	1	2	
Pseudomonas sp.	3.13 (0.75–12.95)	0.7 (0.30–1.60)	–0.73, 0.06 (Ferley et al. 1989) 0.23, 0.08 (Lightfoot 1989)
Range (cfu/100 mL)	0	3	
Number of studies	1	1	
Aeromonas sp.	1.32* (0.31–5.62)	2.40 (1.70–3.39)	–0.43, 0.11 (Ferley et al. 1989)
Range (cfu/100 mL)	190–235	1,549	
Number of studies	2	1	

NS, not statistically significant, *p*-value not provided. [a]Relative risk is the risk versus the summary relative risk for exposed (swimmers) versus unexposed in each category. [b]Values reported represent the correlation between illness and indicator density. *p-Value for test of heterogeneity < 0.2.

Sources of heterogeneity. Several summary relative risks were found to exhibit potentially significant heterogeneity (see notes in Tables 2, 4, and 5). To evaluate possible sources of heterogeneity, an analysis was conducted among studies that examined associations between enterococci and GI illness (Table 6). Water source, adjustment for covariates, study design, length of follow-up period (< 1 week or ≥ 1 week), swimming definition, and geographic location did not significantly contribute to the variation observed in relative risk. Factors that did significantly contribute to the variability in relative risk were selection of control group (nonswimmers vs. swimmers) and type of study population (athletic event participants vs. beach-goers). Summary relative risks for children (under 18) only were elevated compared with studies that included adults or both adults and children together.

Discussion

Epidemiologic studies of the health risks of recreational water have focused on identification of water quality indicators that can predict illness most effectively. An ideal water quality indicator would be simple to measure and would predict illness consistently and accurately in a variety of environments. Moreover, an increase in the concentration of the indicator measure should increase the risk of illness. Based on the epidemiologic studies conducted to date, it is evident that no single indicator can predict illness consistently in all environments at all times, perhaps because of the wide array of pathogens that have been associated with GI illness in recreational water environments as well as natural variability in pathogen–indicator associations. For example, both bacterial and viral indicators of water quality may correlate poorly with the occurrence of protozoan parasites such as *Cryptosporidium parvum*, a leading cause of freshwater outbreaks of GI illness (Barwick et al. 2000; Lee et al. 2002). Taken as a whole, however, the body of literature does support the use of enterococci and *E. coli* as useful predictors of GI illness in marine environments and supports the guideline levels developed by the U.S. EPA. Of the 12 studies in marine water that were above the U.S. EPA enterococci guideline value of 35 cfu/100 mL, eight found statistically significant relative risks of GI illness, and the lowest relative risk observed was 1.31 (Haile et al. 1999). Only two of nine studies with exposures below this level found statistically significant results, and several of these studies found relative risks near or below 1.00 (Fleisher et al. 1993; Foulon et al. 1983; Kay et al. 1994; McBride et al. 1998; Pike 1994). This review also supports the recommended move away from the use of fecal coliform (U.S. EPA 2002) as an indicator because there was no evidence that risk of GI illness increased at levels above the previously

proposed guideline value. In fresh water, *E. coli* was superior to enterococci at predicting illness, and the *E. coli* guideline level was supported, because exposure below presented no significant risk, whereas exposures above were associated with an elevated and statistically significant increased risk of GI illness.

Among the nonfecal indicators of water quality, *Staphylococcus* sp. and *Pseudomonas* sp. are not supported as general predictors of GI illness, whereas the utility of *Aeromonas* sp. remains unclear. Indicators that measure water quality degradation associated with bather shedding such as *Staphylococcus* sp. could be useful in some situations, particularly when the body of water is small, there are many swimmers, and there is little water circulation. *Staphylococci* sp. have been shown to be associated with bather density in swimming pools (Favero et al. 1964), and in an epidemiologic study of a small pond (Calderon et al. 1991), *Staphylococci* sp. was associated with GI illness.

Our results indicate that indicators of viral contamination (enterovirus and bacteriophage) may be promising predictors of GI illness, although this is based on only a few studies. This observation is consistent with reports of norovirus (Norwalk-like viruses)–associated outbreaks in freshwater lakes and swimming pools (Baron et al. 1982; Barwick et al. 2000; Kappus et al. 1982; Lee et al. 2002; Levy et al. 1998). Noroviruses have also been identified in marine waters (Griffin et al. 2003). These viruses are a leading cause of both GI-related outbreaks (Fankhauser et al. 2002) and endemic GI illness (Mead et al. 1999). We found that enteroviruses, which have been suggested as specific indicators of human contamination (Scott et al. 2002), were strongly associated with GI illness. They may, however, be impractical for use as water quality indicators because they are not easily cultivated in environmental samples (Scott et al. 2002).

The analysis of the sources of heterogeneity among the studies provides some insight regarding the impact of study design features on the association between water quality and GI illness. Studies using nonswimming controls had significantly higher relative risks than studies using swimming controls (Table 6). If the risk associated with swimming is of interest, then the appropriate control group should consist of nonswimmers, because a swimming control group may underestimate the risk associated with entering and recreating in the water, resulting in regulatory levels that are too high.

Characteristics of the study population also impacted the relative risk. The elevated relative risk associated with studies of athletic events may be related to the more intense exposure participants in these events experience compared with the exposure of a more typical beach-goer. The finding that studies that focused only on children produced elevated relative risks indicates that children may be particularly susceptible to illness after recreational water exposure. Lower guideline levels may be warranted to adequately protect the health of

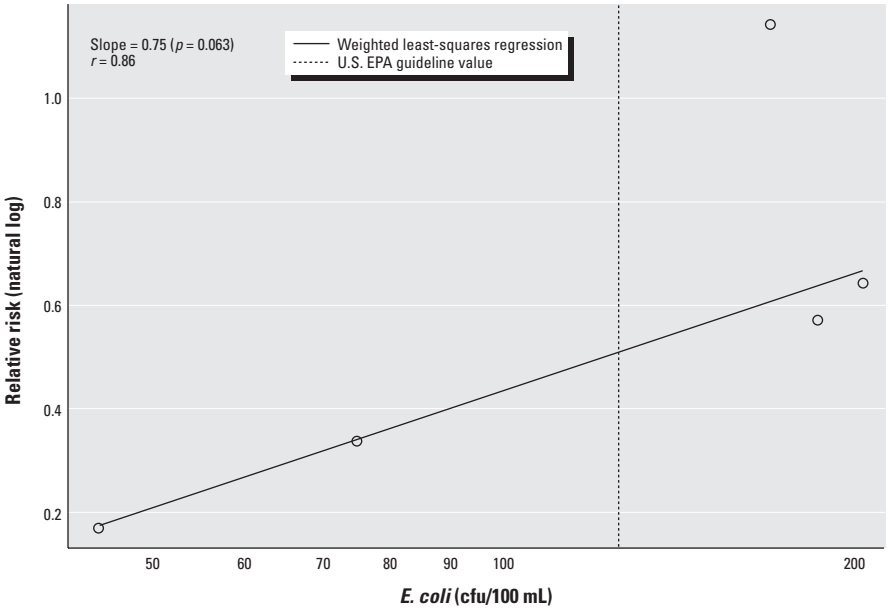

Figure 2. Scatterplot and weighted regression line (weighted by the inverse of the standard error of the natural log relative risk) of the natural log relative risk of GI illness from freshwater studies as a function of *E. coli* density.

Table 5. Summary relative risks by U.S. EPA water quality standards.

Indicator	Current standard (cfu/100mL)	Combined relative risk below standard[a] (95% CI)	Combined relative risk above standard[a] (95% CI)
Marine water			
Enterococci	35	1.36* (0.91–2.03)	2.27* (1.74–2.96)
Number of studies		9	12
Median density (cfu/100 mL)		20	139
E. coli	126	1.33* (0.89–1.99)	1.94* (1.27–2.96)
Number of studies		4	7
Median density (cfu/100 mL)		79	591
Fecal coliform	200	1.74* (0.86–3.53)	1.53* (1.03–2.26)
Number of studies		6	9
Median density (cfu/100 mL)		101	862
Fresh water			
Enterococci	33	1.94* (1.33–2.84)	1.61 (1.32–1.96)
Number of studies		6	2
Median density (cfu/100 mL)		14	858
E. coli	126	1.20 (0.97–1.48)	1.81 (1.47–2.22)
Number of studies		2	3
Median density (cfu/100 mL)		60	187
Fecal coliform	200	1.58* (1.22–2.04)	2.11* (0.98–4.5)
Number of studies		7	3
Median density (cfu/100 mL)		80	285

[a]Relative risk is the risk versus the summary relative risk for exposed (swimmers) versus unexposed in each category. *p-Value for test of heterogeneity < 0.2.

Table 6. Sources of heterogeneity: results from meta-regression models for studies of enterococci and GI illness.

Covariate	Exponentiated regression coefficient (95% CI)[a]
Age of study population (children only studies vs. studies of adults or studies of all ages)	1.85 (1.06–3.19)
Control group (nonswimmers vs. swimmers)	1.88 (1.33–2.67)
Study population (studies of athletic event participants vs. studies of beach-goers or general population)	1.39 (1.05–1.84)

Water quality, as measured by enterococci density, was also included in the model. Thirty-eight point estimates from 20 studies were included in the model. Indicator variables for water source (marine or fresh), study design (randomized controlled trial, cohort, case–control), study location, swimming definition; adjustment for covariates; and follow-up times were included in the initial model but were removed since they were not significantly associated to the relative risk ($p > 0.2$). Exponentiated coefficients can be interpreted as the impact (on a multiplicative scale) on the relative risk.

children (and other susceptible individuals) and events resulting in prolonged exposure.

Suggested further research. No studies to date have specifically examined the impact of recreational water exposure on persons whose immune systems are compromised because of HIV infection or other conditions. Studies focusing on immunocompromised persons would ultimately provide valuable information towards developing enhanced water quality guidelines for susceptible individuals. Also, although studies of children have been conducted, their susceptibility needs to be better defined.

Research is needed to better understand the ability of rapid and specific microbial methods to predict illness. Standard membrane filtration methods for enterococci require 24-hr incubation (U.S. EPA 1997), making it impossible for recreational water managers to respond quickly to changes in water quality. The use of rapid microbial methods, such as real-time polymerase chain reaction (PCR), could help managers respond more quickly and effectively, but these methods have yet to be studied in conjunction with health effects. Microbial source tracking methods include both phenotypic (e.g., grouping based on antibiotic resistance patterns, or serotype) and genotypic methods (e.g., pulse field gel electrophoresis, PCR, ribotyping, and host-specific molecular markers) (Scott et al. 2002). These methods should be incorporated into future epidemiologic studies to assess the relative impact of human versus nonhuman contamination on illness.

An epidemiologic study that combines self-reported illness symptoms with serology tests for GI pathogens could help identify the specific pathogens responsible for any observed increase in illness. Stool specimens collected from symptomatic (and/or asymptomatic) subjects would also provide valuable pathogen specific information.

Limitations. As with any meta-analysis, the summary relative risks reported should be interpreted cautiously, particularly because significant heterogeneity was noted. As a result, we used a conservative random effects model, which takes into account both within- and between-study variability, to determine summary relative risk and their 95% confidence intervals.

Publication bias—the preferential publication of papers reporting an association—can be a problem with any systematic review or meta-analysis. Although we tried to minimize the potential for publication bias by obtaining unpublished reports and dissertations, it is possible that some unpublished studies were not available for this review. A statistical test (Begg and Madachhanda 1994) indicated a borderline significant rank correlation ($p = 0.09$) between the log relative risk and the sample variance, an indication of publication bias. As a result, it is possible that the summary relative risks reported here are overestimates, but the true effect of this bias is impossible to evaluate completely.

This review focuses only on GI illness, which, despite being the most extensively studied, may not necessarily be the most appropriate or sensitive health outcome on which recreational water quality guidelines should be based. We are also examining other health outcomes and their relationship to water quality, and plan to report these in future analyses.

Conclusions

Our review suggests that enterococci and, to a lesser extent, *E. coli* are adequate indicators of GI illness in marine water, but fecal coliforms are not. There was evidence that risk of GI illness was considerably lower in studies with indicator densities below the guidelines proposed by U.S. EPA for both enterococci and *E. coli*, providing support for use of these values for regulatory purposes. In fresh water, *E. coli* was a more reliable and consistent predictor of GI illness than is enterococci.

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